BAD DESIGN DECISIONS

Why do we make them?

George A. Hazelrigg
Program Director, Design and Integration Engineering
National Science Foundation

Let's meet to decide which design is best

3 designs (A, B, C), 15 people in the meeting

Votes: A 6, B 5, C 4; A wins, C loses

6 people: A is preferred to C is preferred to B
5 people: B is preferred to C is preferred to A
4 people: C is preferred to B is preferred to A

But:

A vs. B		A vs. C		B vs. C	
6	5	6	5	5	6
	4		4		4
6	9	6	9	5	10

The group's preference is C over B over A

Let's go to the customers to see what they want

5 designs (A, B, C, D, E) judged by 100 people
   Result: A, 45; B, 25; C, 17; D, 13; E, 0   (8,933,551 possible)

A set of preferences that support this result ($\sim 10^{62}$ possible):
   45 people: A E D C B
   25 people: B E D C A
   17 people: C E D B A
   13 people: D E C B A

Results of pairwise comparisons:
   E is preferred to A (55/45), B (75/25), C (83/17), D (87/13)
   D is preferred to A (55/45), B (75/25), C (83/17)
   C is preferred to A (55/45), B (75/25)
   B is preferred to A (55/45)

The group preference ordering is E D C B A

I'm just going to make my bosses happy

- I have three bosses I report to on this project

- I have three design alternatives to choose from, A, E and P

- I'll just pick the alternative that makes my bosses happy

Boss mania

Individual	Preferences	Choices		
		A vs. *P*	*P* vs. *E*	*A* vs. *E*
I	*A>P>E, A>E*	A	P	A
II	*P>E>A, P>A*	P	P	E
III	*E>A>P, E>P*	A	E	E
Group preferences:		*A>P*	*P>E*	*E>A*

E is preferred to *A* 2:1
P is preferred to *E* 2:1
*A* is preferred to *P* 2:1

There is no preferred design

Transitivity

Consider the case A>B>C>A

- A decision maker with these preferences is said to be irrational. The preference ordering is intransitive. No decision can be made in accord with these preferences.

If A>B>C, then also A>C

- If this condition is met, the decision maker is rational, the preferences are transitive, and decisions are possible.

- Groups consisting of rational individuals can have intransitive group preferences
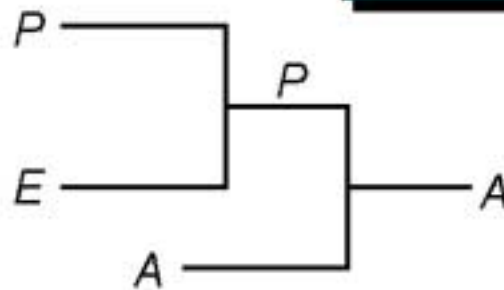
A
apple

B
pear

C
orange
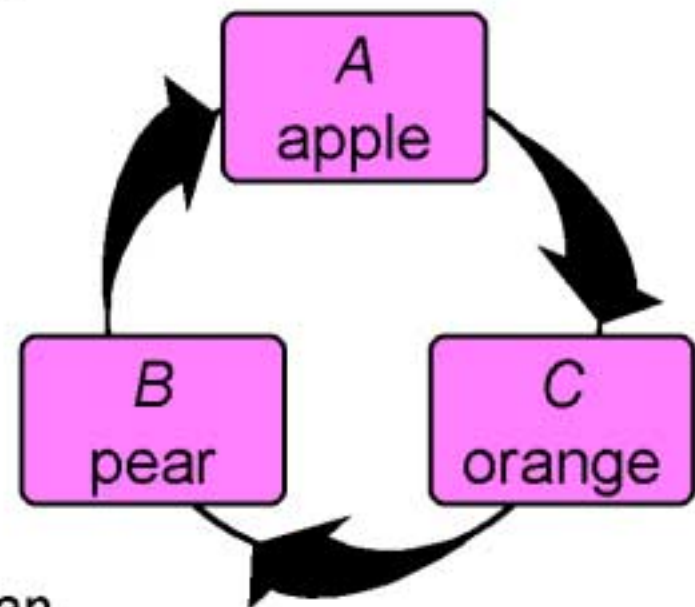
Boss mania--the best design
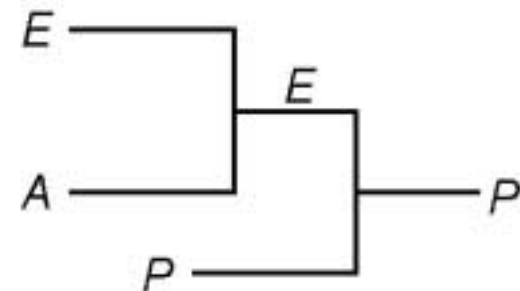
A ⎤
   ⎤ A
P ⎦ ⎦————— E
    ⎤
E ⎦
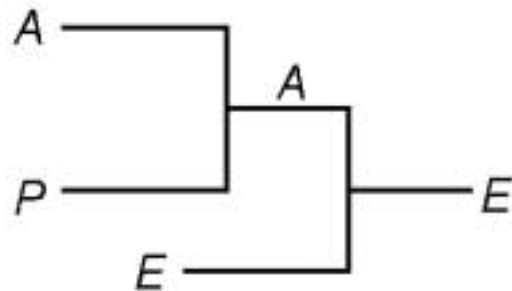
This method of voting is called "Best of the Best." It is in common use (e.g., sports). It is the worst method to use to seek a choice.

Preferences:
A over P
P over E
E over A

P ⎤
  ⎤ P
E ⎦ ⎦————— A
   ⎤
A ⎦

The alternative voted upon last has the best chance of winning.

E ⎤
  ⎤ E
A ⎦ ⎦————— P
   ⎤
P ⎦

The concept of preference

Preferences rank order outcomes

- An objective function maps outcomes onto the real number line (scalar) in accordance with the decision maker's preferences. The preferred choice is that alternative whose scalar value measure is the greatest
  - The scalar measure must rank order all pairs of outcomes
  - If preferences are intransitive, this mapping is impossible, and optimization cannot be accomplished

Preferences in optimization:

Max $f = -x^2$
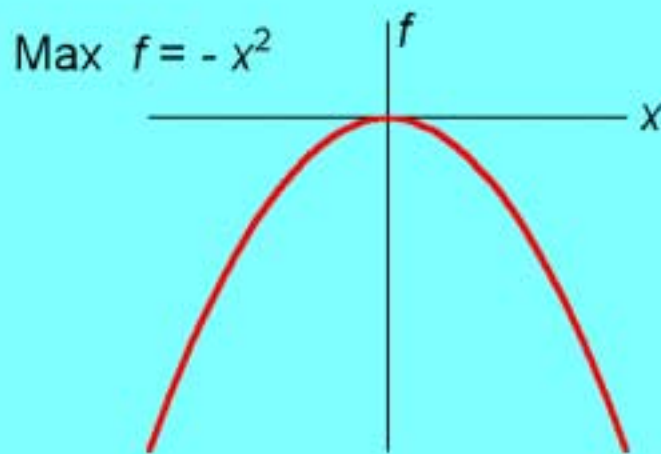
Table of comparisons:

$x =$	$f =$
1	-1
2	-4

f is a scalar measure that enables comparison of values of x, and the selection of the most preferred value of x

The test of a preference function is to see if it rank orders all outcomes the same as would the decision maker.

I'll just use a scoring technique...

- Four materials, A, B, C, D. Which is best? Five tests run twice.

> Test I: A > C > B > D
> Test II: A > C > B > D
> Test III: B > A > C > D
> Test IV: B > A > C > D
> Test V: B > A > C > D

Scores:
  A: 3+3+2+2+2 = 12
  B: 1+1+3+3+3 = 11
  C: 2+2+1+1+1 = 7
  D: 0+0+0+0+0 = 0

A is best

and just to be sure I got the right answer...

- Second set of tests. This time material C is left out of the testing process. Tests on A, B and D give exactly the same results as in the previous set of tests.

Test I: A > B > D
Test II: A > B > D
Test III: B > A > D
Test IV: B > A > D
Test V: B > A > D

Scores:
   A: 3+3+2+2+2 = 12
   B: 2+2+3+3+3 = 13
   D: 1+1+1+1+1 = 5

B is best

But real designs have multiple attributes

Customer	Attribute					
	Size		Shape		Color	
	Large	Small	Flat	Bumpy	Red	Green
John	Hate	Great	Great	OK	Great	OK
Pam	Great	OK	Hate	Great	Great	OK
Trevor	Great	OK	Great	OK	Hate	Great
Preference	Large		Flat		Red	

Potential market--
    Large, Flat, Red (LFR)   0
    Small, Bumpy, Green (SBG)   3
SBG is clearly a better design than LFR

The optimal product attributes are not the most preferred attributes

Maybe I should use the Pugh method

Customer	Attribute Utility					
	Size		Color		Shape	
	Large, L	Small, S	Red, R	Green, G	Flat, F	Bumpy,B
Tom	0	1	1	.9	1	.9
Pat	1	.9	0	1	1	.9
Jan	1	.9	1	.9	0	1

- 8 possible designs: LRF, LRB, LGF, LGB, SRF, SRB, SGF, SGB
- Customers have multiplicative value functions (rational customers)

Pugh phew

Attribute	Product design							
	LRF	SGB	SGF	SRB	SRF	LGB	LGF	LRB
Size	L	–	–	–	–	0	0	0
Color	R	–	–	0	0	–	–	0
Shape	F	–	0	–	0	–	0	–
Tom	0	.81	.9	.9	1	0	0	0
Pat	0	.81	.9	0	0	.9	1	0
Jan	0	.81	0	.9	0	.9	0	1
Pot. Mkt.	0	3	2	2	1	2	1	1

(left vertical label for the Tom/Pat/Jan rows: Utility)

- Pugh selection is exactly opposite, it has rank ordered designs precisely wrong

Forget this, I'll use agents

- Five agents make a decision to choose one of three alternatives, A, B or C:

    - Agent 1: A>B>C
    - Agent 2: B>C>A
    - Agent 3: C>A>B
    - Agent 4: A>C>B
    - Agent 5: B>C>A

- Method of choice   Result

    (A vs. B) vs. C   C
    (B vs. C) vs. A   A
    (A vs. C) vs. B   B
    Borda count   Tie
    Condercet   Every choice is the worst
    1 person, 1 vote   A, B tie, C loses, A wins runoff vote
    1 person, 2 votes   C wins

- Conclusion: Preferences of the agents alone cannot determine the outcome; the voting process, not the preferences determines the outcome

- The behavior of the agents is totally chaotic

Hey, the problem with your examples is that you just used the wrong scoring techniques. Do it right, and these problems won't occur.

Arrow's Impossibility Theorem

- A constitution is a voting rule

- Desired conditions
  - *Transitivity*--if the group prefers x to y and prefers y to z, then the constitution should prefer x to z
  - *Unanimity*--if every member of the group prefers x to y, then the constitution should prefer x to y
  - *Independence of irrelevant alternatives*--the constitution should rank x and y based only on the preferences of the group between x and y
  - *Dictatorship*--the constitution should not be such that whenever individual n prefers x over y, the constitution prefers x over y

- Arrow's Impossibility Theorem--Any constitution that respects transitivity, unanimity and independence of irrelevant alternatives is a dictatorship as long as there are at least 3 alternatives. I.e., it ain't possible to find the "right" scoring technique

- Kenneth Arrow, professor/economist, Stanford University, Nobel Prize in economics, 1972.

So, where are the problems?

- The only way to draw correct conclusions from survey data is to preserve the full preference orderings (we don't bother to collect these)
- You can't aggregate preferred attributes into a product and expect the product to be preferred at all, let alone optimal
- Because of the above problems, you can't even collect preference orderings in most real cases (10 attributes, 5 instantiations of each yields 5^{10} = 9,765,625 different designs)
- You can't expect any scoring or voting method to give results consistent with the data
- You can't optimize a design for multiple bosses or multiple customers
- There is no such thing as "multi-objective" decision making or design
- You can expect agents to behave chaotically, this includes multiple systems engineers working remotely

More often, the cause of bad engineering design decisions is a bad decision method, not bad data

Wait, we're not done, it gets worse

Question: What about uncertainty? Design involves decision making under uncertainty and risk.

Let's keep the system mass under control

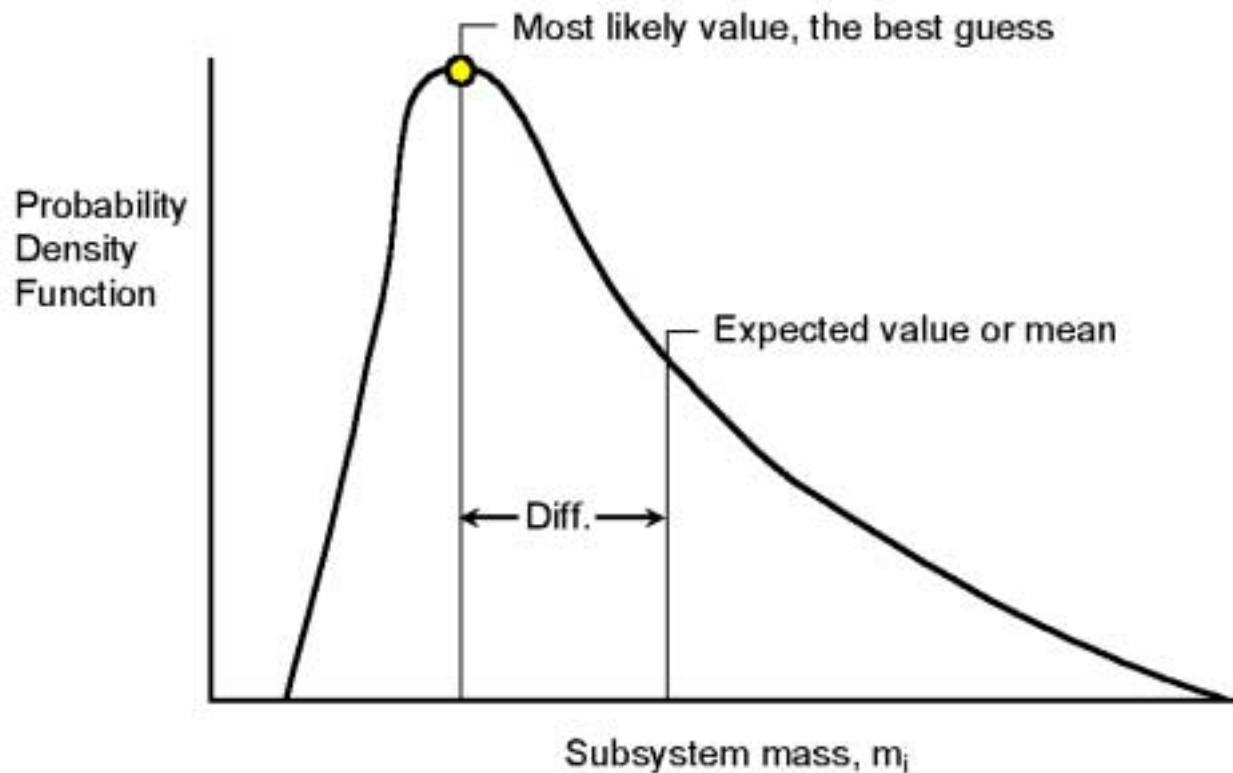What will be the system mass if I design it this way?

A model:

$$m_{sys} = \sum m_i = m_1 + m_2 + m_3 + ...$$

Problem: The m_i are random variables (functions) and addition (+) is undefined for random variables. It is legitimate only to add numbers, such as expected values of random numbers. Thus,

$$E\{m_{sys}\} = \sum E\{m_i\} = E\{m_1\} + E\{m_2\} + E\{m_3\} + ...$$

is a correct expression.

But everyone just adds the masses, so?

Probability Density Function — Subsystem mass, m_i. Most likely value, the best guess. Expected value or mean. Diff.

- Neglect of uncertainty leads to a systematic error that always results in the underestimation of system mass (and cost)

- Neglect of uncertainty always leads to overly rosy conclusions

Just how bad can neglect of uncertainty be?

- The way we usually do it --
  $$a = \text{Best guess}\{f\}/\text{Best guess}\{m\}$$

- The way it is --
  $$E\{a\} = E\{f\} \times E\{1/m\}$$

- The difference -- an example: take $f = 1$ (deterministic), m is a random variable flatly distributed on the interval 0 to 1

  $$a = \text{Best guess}\{f\}/\text{Best guess}\{m\} \Rightarrow 2$$

  $$E\{a\} = E\{f\} \times E\{1/m\} \Rightarrow \infty$$

The error resulting from neglect of uncertainty is unbounded

So, where does this leave us?

- Our goal is to make design decisions that are consistent with what we know. To do this
  - We must take care to be mathematically rigorous in everything we do relative to design
  - We cannot rely on ad hoc methods
  - We must take uncertainty into account properly

- But take heart, the mathematics has already been done for us
  - Probability theory
  - Decision theory
  - Economics

- The job facing us is to implement it correctly for engineering design and systems engineering
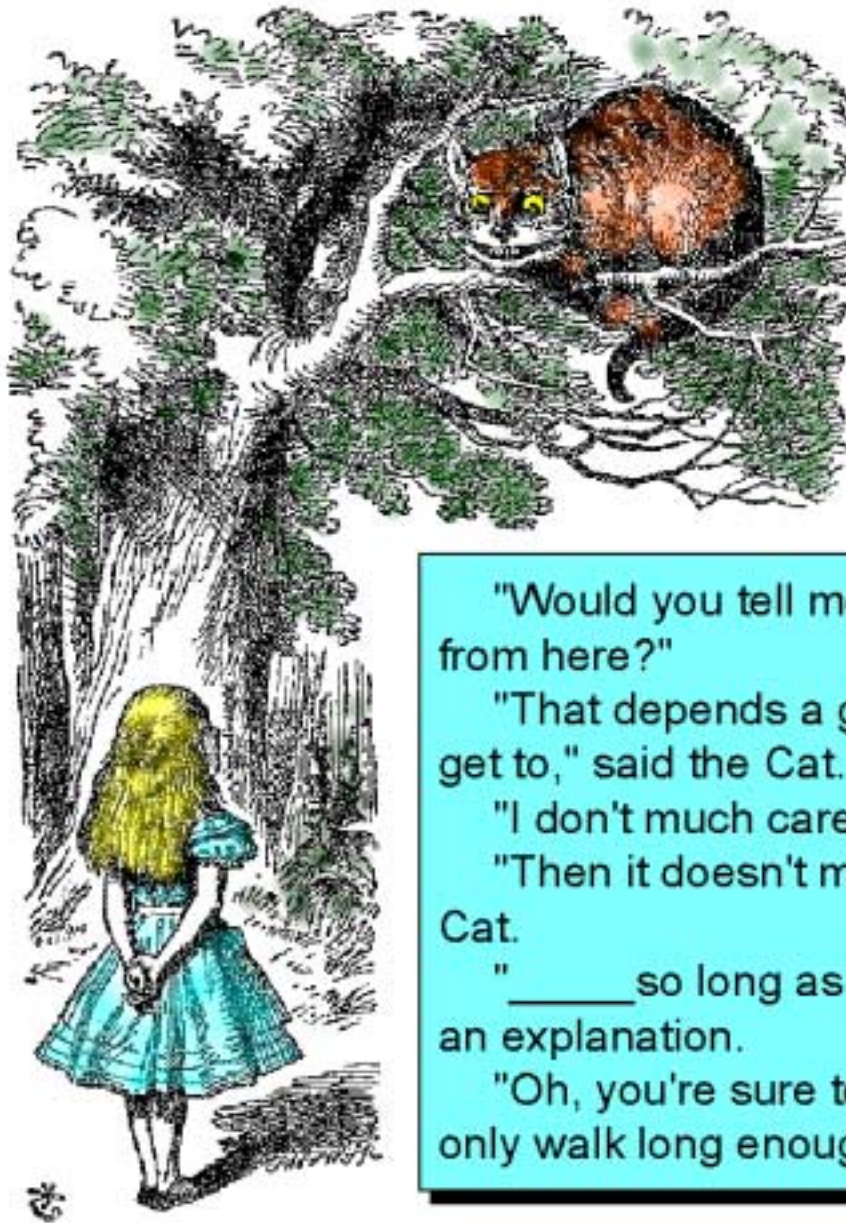
"Would you tell me, please, which way I ought to go from here?"

"That depends a good deal on where you want to get to," said the Cat.

"I don't much care where_____" said Alice.

"Then it doesn't matter which way you go," said the Cat.

"_____so long as I get *somewhere*," Alice added as an explanation.

"Oh, you're sure to do that," said the Cat, "if you only walk long enough."

Carroll's Points

- *Quote:* "That depends a good deal on where you want to get to."

  - **Lesson 1:** All decisions are made based on preferences.

  - **Lesson 2:** The (only) preferences that matter are those of the decision maker.

  - **Lesson 3:** Preferences are on outcomes.

- *Quote:* "Then it doesn't matter which way you go."

  - **Lesson 4:** Don't try to distinguish between alternatives on the basis of outcomes upon which the decision maker has no preferences.

- *Quote:* "Oh, you're sure to do that if only you walk long enough

  - **Lesson 5:** Decisions cannot be avoided. Outcomes will occur.

Classical normative decision theory

Given a defined set of alternatives from which to choose, each with a known and deterministic outcome, the decision maker's preferred choice is that alternative whose outcome is most desired.

Good decisions, bad decisions

- There is a difference between good or bad decisions and good or bad outcomes.

- Example: Bet $2 on the flip of a fair coin. Win $5 if you choose heads and heads occurs. Win $3 if you choose tails and tails occurs. Win nothing otherwise.

Outcome

Bet
-$2

H
- H, +$3
- T, -$2

T
- H, -$2
- T, +$1
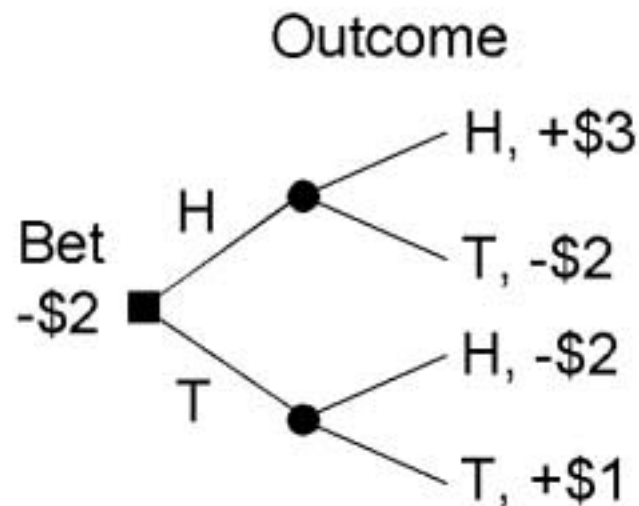
Outcome

Decision	H	T
H	Good decision, good outcome	Good decision, bad outcome
T	Bad decision, bad outcome	Bad decision, good outcome

Decisions, expectations and outcomes
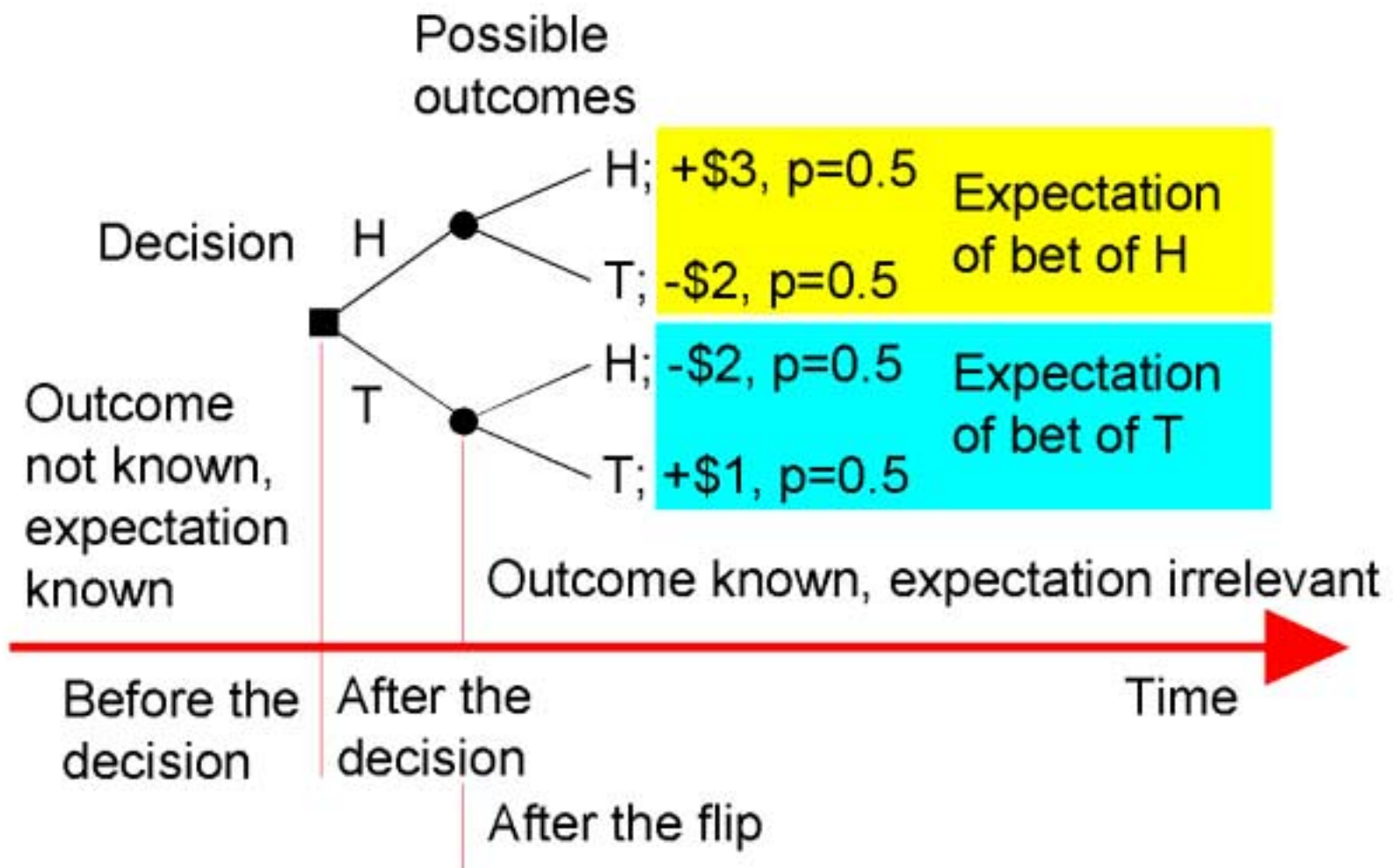
von Neumann and Morgenstern, 1940s

Six axioms that provide a normative theory of decision making under uncertainty and risk

- Outcomes can be ordered in terms of preferences of the decision maker, and the ordering is transitive
- Compound lotteries can be reduced to simple lotteries
- Continuity of preferences exists
- A lottery consisting of several possible outcomes can be reduced to an equivalent lottery that has only two possible outcomes
- Preferences among lotteries are transitive
- Given two otherwise identical lotteries, each with two possible outcomes, the preferred lottery is the one whose probability of the preferred outcome is higher

Expected utility theorem

Given a pair of alternatives, each with a range of possible outcomes and associated probabilities of occurrence, the preferred choice is the alternative that has the higher expected utility.

Four Steps to a Decision

- Determine your preferences--what do you want

- Generate alternatives--generation of alternatives is focused by your preferences

- Generate expectations on each alternative

- Select the preferred alternative based on your preferences

ALL decision methods/tools invoke these four steps

Favorable properties of a design method

1. The method should provide a rank ordering of candidate designs.
2. The method should not impose preferences on the designer.
3. The method should permit the comparison of design alternatives under conditions of uncertainty and with risky outcomes.
4. The method should be independent of the discipline of engineering.
5. If the method recommends alternative A when compared to the set of alternatives $S=\{B,C,D,...\}$, then it should also recommend A when compared to any reduced set such as $S_R=\{C,D,...\}$.
6. The method should make the same recommendation regardless of the order in which the design alternatives are considered.
7. The method should not impose constraints on the design or the design process.
8. The method should be such that the addition of a new design alternative should not make existing alternatives appear less favorable.
9. The method should be such that information is always beneficial.
10. The method should not have internal inconsistencies.

Key Points

✔ Neophytes beware!

✔ The world is full of bad design methods (QFD, Pugh, AHP, Taguchi, Six Sigma, weighted sum of attributes,...)

✔ It's no easier to conjure up a valid design method than it is to develop a valid theory in quantum mechanics

✔ Bad design methods are essentially random selection techniques, that is, they are no better than the use of random numbers to make design decisions

✔ In fact, bad methods are dangerous--they trick us into making bad decisions even sometimes when it is obvious that the decisions are bad

✔ The mathematics of probability theory and decision theory provide a basis for the development of sound design methods

✔ To make good design decisions, we must have good design decision methods; to get good methods, we must employ good mathematics--it isn't easy, but we have no choice

It is more likely that bad design decisions are the result of bad methods than the result of bad information or bad data